

State of California
The Resources Agency
Department of Water Resources
DIVISION OF DESIGN AND CONSTRUCTION

**REVIEW OF SEISMIC STABILITY ISSUES
FOR SACRAMENTO-SAN JOAQUIN DELTA LEVEES**

Briefing Paper Prepared for the
California Bay-Delta Oversight Council



Memorandum Report

October 1993

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Secretary for Resources
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REVIEW OF SEISMIC STABILITY ISSUES
FOR SACRAMENTO-SAN JOAQUIN DELTA LEVEES

DIVISION OF DESIGN AND CONSTRUCTION
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for

The California Bay-Delta Oversight Council

FOREWORD

This memorandum report is intended as a briefing paper for the Bay-Delta Oversight Council on seismic stability issues associated with levees in the Sacramento-San Joaquin Delta. Most of the information in this report has been obtained from the Department's 1992 Phase I report entitled **"SEISMIC STABILITY EVALUATION of the SACRAMENTO-SAN JOAQUIN DELTA LEVEES - Preliminary Evaluations and Review of Previous Studies."** Further details and references can be obtained in the 1992 report.

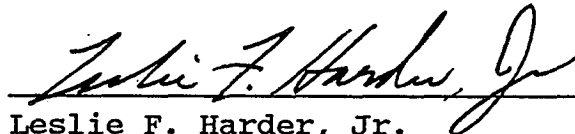
The studies were performed with guidance from a Board of Consultants established by the Department. This board consists of three experts in the fields of seismology, earthquake engineering, and geotechnical engineering.

The evaluations were performed to provide information as to the susceptibility for Delta levees to sustain damage during earthquakes. With this information, the degree of risk can be estimated in a general way and a rational approach can be pursued in the management of existing and future Delta facilities and resources.

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The Resources Agency
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ENGINEERING CERTIFICATION

This report has been prepared under my direction as the professional engineer in direct responsible charge of the work, in accordance with the provisions of the Professional Engineers' Act of the State of California.



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Date: October 8, 1993



TABLE OF CONTENTS

	<u>Page</u>
FOREWORD	iii
ENGINEERING CERTIFICATION.....	iv
1. EXECUTIVE SUMMARY	1
2. LEVEE HISTORY AND PERFORMANCE OF LEVEES DURING EARTHQUAKES	4
2.1 Regional Geology	4
2.2 Levee Construction and Island Reclamation	4
2.3 Potential Modes of Earthquake-Induced Levee Failure	6
2.4 Liquefaction and Strength Loss	6
2.5 Prominent Examples of Earthquake-Induced Levee Failures	8
2.6 Historical Seismicity in the Sacramento- San Joaquin Delta Area	9
2.7 Performance of Delta Levees During Previous Earthquakes	9
3. SEISMIC ENVIRONMENT	12
3.1 Active Faults	12
3.2 Probability of Future Earthquakes.....	12
3.3 Probable Bedrock Motions Beneath Delta Within 30 years	16
4. GROUND MOTION AMPLIFICATION/DAMPING.....	18
4.1 Amplification through Soft Clays in San Francisco during 1989 Loma Prieta Earthquake	18
4.2 Damping through Soft Peats in Union Bay, WA during 1969 Earthquake Sequence	18
4.3 Implications for Delta Levees	21
5. PREVIOUS STUDIES	22
5.1 General	22

TABLE OF CONTENTS (continued)

	<u>Page</u>
6. PRELIMINARY ASSESSMENT OF LEVEE DAMAGE POTENTIAL.....	26
6.1 General	26
6.2 Preliminary Assessments of Levee Damage Potential	27
6.3 Damage Potential for Eight Key Western Delta Islands	27
6.4 Methods Available to Strengthen Levees Against Earthquakes	30
7. FUTURE STUDIES.....	31
7.1 Purpose and Need	31
7.2 Installation of Surface and Subsurface Seismographs	32
7.3 Laboratory and Field Testing of Organic Soils	32

1. EXECUTIVE SUMMARY

The islands in the Sacramento-San Joaquin Delta lie commonly 10 to 15 feet below sea level and are protected by levees against inundation from the adjoining rivers and sloughs. The original levees were constructed in the late 1800s to have heights of about five feet and were generally founded on soft, organic soils common in the Delta. Due to continued settlement of the levees and subsidence of the island interiors, it was necessary to continually add material to the levees in order to maintain freeboard and structural stability. Over the last century, the levees have significantly increased in size and now are commonly between 15 and 25 feet in height.

Most of the levees were built of non-select, uncompacted materials which were added piecemeal in lifts and/or berms. The sidedraft-clamshell dredge was commonly used to build the levees and is still used today to maintain them. The resulting structures are embankments composed of mixtures of uncompacted sands, silts, clays, and organic soils. There has often been a concern for the performance of these levees during earthquakes, as similar structures commonly experience liquefaction and damage during moderate to strong earthquake shaking. Concern has also been raised concerning the liquefaction potential of foundation materials at some islands.

Since reclamation of the Delta began in the late 1800s, bedrock and stiff soil lying beneath the soft organic soils common throughout the Delta have not been subjected to significant earthquake-induced ground motions (accelerations greater than 0.1g). No record of a levee failure, or even significant damage to a levee as a result of earthquake shaking has been found. This indicates that the Delta levee system has never been significantly tested for earthquake shaking. However, there are several active faults located to the west of the Delta which are capable of delivering moderate to large shaking (e.g. Antioch, Greenville, and Coast Range Sierra Nevada Boundary Zone Faults). Such motions could be significantly larger than the relatively small levels of ground motion that the Delta has experienced since the levees were constructed.

Several preliminary studies of the seismic stability of Delta levees have been completed in recent years. Such studies are preliminary in nature because of the long lengths of levees involved (over 1,100 miles), the lack of information

SEISMIC STABILITY OF DELTA LEVEES

concerning the levees and their foundations, and the great unknowns related to the capabilities of the organic soils beneath the levees to either amplify or attenuate ground motions. Nevertheless, most of the studies seem to conclude that levee failure would result if surface motions exceeded some critical acceleration, generally reported to be between 0.1g and 0.2g.

The amount of levee damage and/or failure which would be predicted involves several factors. Two of the principal factors involve the period of exposure and the amount of ground motion amplification which could be experienced in the foundations beneath the levees. Both of these parameters basically involve the level of shaking which the levee would experience. For longer periods of exposure, larger ground motions would be expected to be experienced. This is analogous to recurrence intervals used for storm flood analyses (e.g. 100-year flood). Several seismic studies have used a 30-year exposure period, partly because the United States Geological Service has predicted that a large magnitude ($M > 7$) would have a two-thirds chance of occurring in the San Francisco Bay Area during this period.

The consensus of several studies would seem to suggest that there would probably be levee damage and failure induced in the Delta by earthquake shaking within the next 30 years. Studies by the Department of Water Resources suggest that moderate to moderately high damage and levee failure would be expected during this time period along the western edge of the Delta.

The consequences of levee failure and island inundation depend upon the location of the inundated island and the flow conditions at the time of failure. When a Delta levee fails, water from the adjoining rivers and channels flow toward the island which is flooding. This may lead to reverse flows in some channels and draw salt water deeper into the Delta. During typical winter flood flows there is generally so much flow moving towards the San Francisco Bay that salt water is generally not pulled into the Delta. However, during low flow conditions, salt water intrusion is quite possible. The result could be so much salt water intrusion that water export might have to be halted and increased upstream reservoir releases might be necessary to dilute and flush out the intruded saline water. Unlike many levee failures during winter floods, an earthquake-induced levee failure during low flow conditions (e.g. drought or summer months) could seriously disrupt water deliveries.

Further investigations involving field and laboratory testing are needed to reduce the uncertainties and better define the expected performance of the levees during future earthquakes. In particular, the ability of the soft organic soils beneath the levees to either amplify or dampen motions needs to be determined. This material property significantly affects the predicted performance of the levees and our understanding of this property is severely limited at this time.

2. LEVEE HISTORY AND PERFORMANCE OF LEVEES DURING EARTHQUAKES

2.1 REGIONAL GEOLOGY

The Sacramento-San Joaquin Delta, located at the confluence of the Sacramento and San Joaquin Rivers, is part of a large basin commonly known as the Central Valley of California. In recent geologic time, this area has undergone several cycles of deposition and erosion, resulting in the accumulation of a few hundred feet of poorly consolidated to unconsolidated sediments.

Delta peats and organic soils began to form about 11,000 years ago during one of the rises in sea level. This rise in sea level created tule marshes that covered most of the Delta. Peat formed from repeated burial of the tules and other vegetation growing in the marshes. Presented in Figure 1 is an organic isopach map of the Delta showing the different thicknesses of organic soils throughout the Delta. In general, the thicknesses of these soft soils range between 0 and 50 feet, but are commonly about 10 to 30 feet throughout most of the Delta.

During the cycles of erosion and deposition, streams were entering from the north, northeast, and southeast. These included the Sacramento, Mokelumne, and San Joaquin Rivers. As the rivers merged, they formed a complex pattern of islands and interconnecting sloughs. River and slough channels were repeatedly incised and backfilled with sediments with each major fluctuation. Along many of these channels, sediment deposited during overbank flows formed small, natural levees composed of intermixed mineral and organic soils.

2.2 LEVEE CONSTRUCTION AND ISLAND RECLAMATION

During the late 1800s, Delta inhabitants began fortifying existing natural levees and draining inundated islands in the Delta for agricultural use. Most of the early levees in the Delta were constructed by Chinese laborers using hand shovels and wheelbarrows, and some were built using scrapers pulled by horses. Later, the sidedraft-clamshell dredge was used. The levees were generally built of non-select uncompacted materials without engineering design and without good construction methods. The original levees were usually less than five feet high, but settlement of the levees and subsidence of the interior island soils have required the

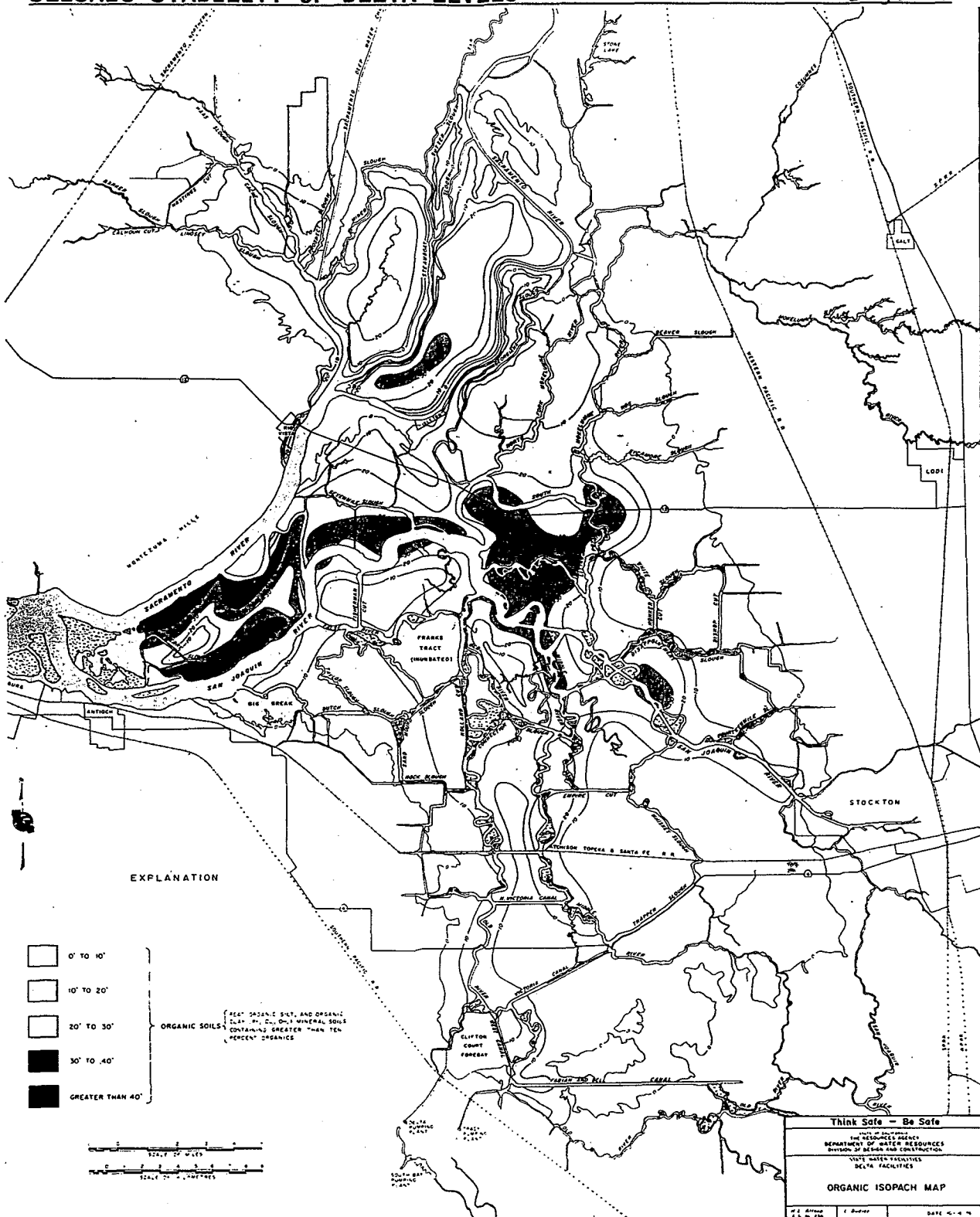


FIGURE 1: ORGANIC ISOPACH MAP OF THE DELTA (from DWR, 1976)

continued addition of fill on the levees to maintain protection against overtopping by waters of the Delta.

The interiors of many islands are now commonly 10 to 15 feet below sea level. Presently, some levee crowns are 20 to 25 feet higher than the interior of their respective islands. In order to maintain stability of the high embankments over the relatively soft soils in the Delta, large berms or buttresses have had to be added to the levee sections. This process has resulted in the original 5-foot-high levees growing into relatively large embankments. Figure 2 illustrates the development process that many typical Delta levees have experienced.

2.3 POTENTIAL MODES OF EARTHQUAKE-INDUCED LEVEE FAILURE

Levee failure is defined as sufficient levee distress as to result in inundation of the protected area, in this case a Delta island or tract. For earthquake shaking to induce a levee failure, one of the two general failure modes must occur:

- o Earthquake shaking produces sufficient deformation or settlement in a levee and/or its foundation to result in its being overtopped and washed away by the waters it is retaining.
- o Earthquake shaking produces sufficient deformation or settlement in a levee and/or its foundation to result in severe cracking of the levee. Such cracking then allows water to seep through the levee along preferred paths and gradients that result in internal erosion and the piping away of the embankment.

2.4 LIQUEFACTION AND STRENGTH LOSS

Many types of soils that are dry or dense exhibit no strength loss during the cyclic loadings common to earthquakes, and structures composed of or founded on such soils behave well. However, soils which are soft and/or loose and saturated often lose considerable strength during cyclic loadings. The ultimate strength loss is known as **LIQUEFACTION** and is a state in which the soil loses most of its original strength and behaves essentially as a viscous liquid. Loose, cohesionless soils such as sands and silts below the ground water level commonly liquefy during earthquakes. There have been several instances where structures or embankments built

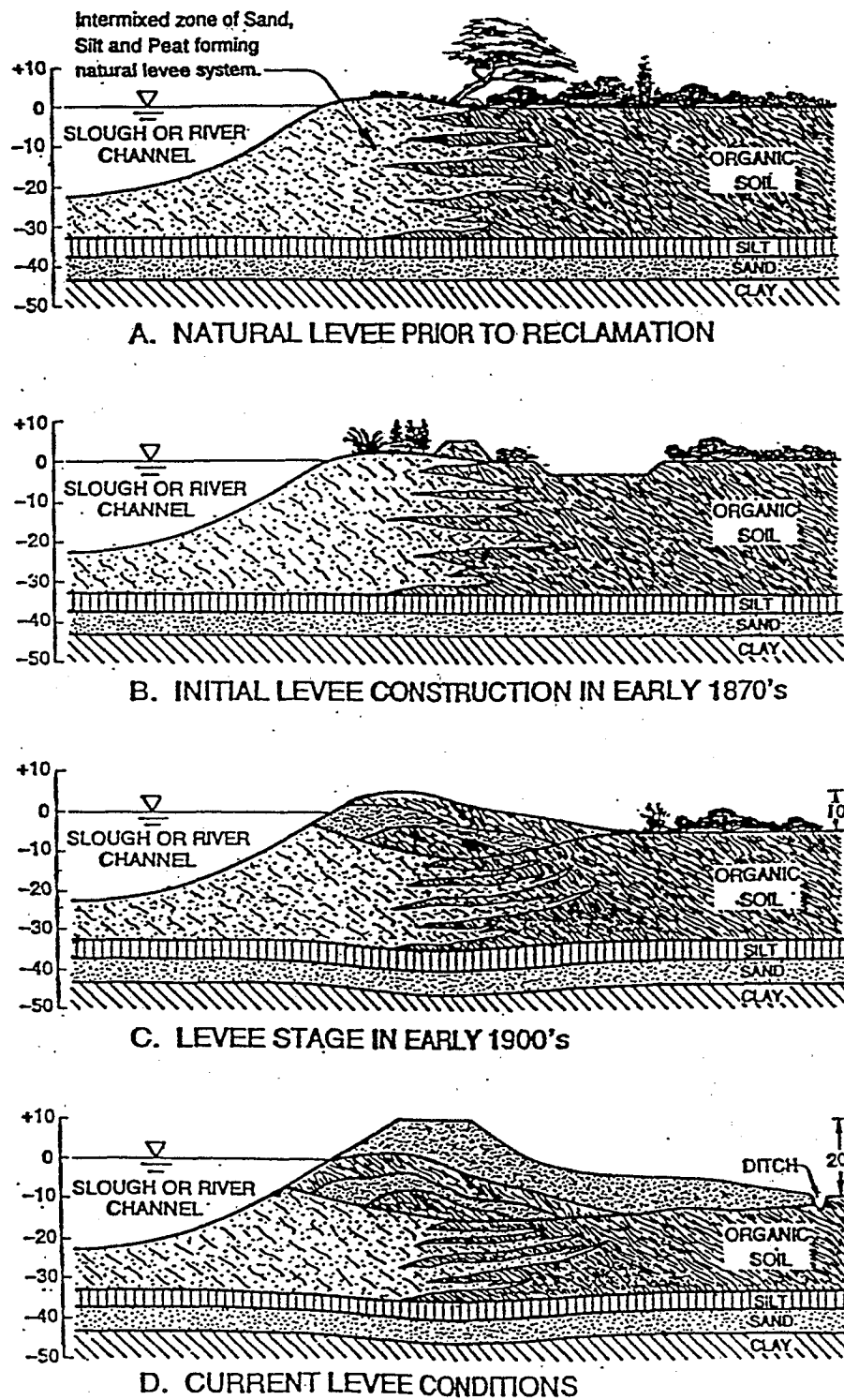


FIGURE 2: DEVELOPMENT OF DELTA LEVEES (from DWR, 1992)

on such soils have experienced dramatic failures due to soil liquefaction.

Liquefiable soils are generally found in recent deposits along rivers and estuaries, and in man-made deposits such as hydraulic fills. It appears generally well-established that at least some of the levees in the Delta contain liquefiable soils and that there are also locations where river sediments which form the foundations of levees are also susceptible to liquefaction.

There is very little available information, however, to help determine if the organic soils comprising some of the levees and their foundations are susceptible to significant strength losses.

2.5 PROMINENT EXAMPLES OF EARTHQUAKE-INDUCED LEVEE FAILURES

In many areas of the world, levees which sustain medium to strong earthquake shaking commonly experience significant damage. This is because levees are often built of loose materials, are saturated because they retain water, and liquefy whenever earthquake shaking is high enough. Listed below are two prominent examples of levee failures which occurred when earthquake shaking induced liquefaction within either the levee fill or its foundation:

Solfatara Canal Levee

The Solfatara Canal is located in Mexico south of the California border near Mexicali. On May 18, 1940, a Magnitude 7.1 earthquake occurred along the Imperial Fault running from California south through Mexico. Approximately 12 miles of this canal levee were essentially destroyed by very strong earthquake shaking. Levee embankments settled as much as seven feet into their foundations, leaving very little residual fill to retain canal water (see Figure 3). There was also extensive damage to the levees of the All-American, Alamo, and Cerro Prieto Canals in this area following the earthquake.

Moss Landing Tide Gate Embankment

The Moss Landing Tide Gate Embankment is an embankment constructed across an estuary near Moss Landing, California. The purpose of the embankment is to provide vehicle access to the Moss Landing State Beach. A culvert pipe had been placed within the embankment to

allow estuarial tidal flows to pass through the embankment. During the 1989 Loma Prieta Earthquake, the site experienced moderate earthquake shaking with peak accelerations estimated to be about 0.25g. This triggered a liquefaction flow failure of the embankment, resulting in approximately 4 feet of settlement (see Figure 4). As the embankment was only about 6 feet high, most of the entire height of this levee-like embankment was lost as a result of the earthquake.

The above examples of embankment behavior are cited because of similarities between the embankments and many levees which exist in the Delta. Both embankments retain channel or estuarial water and have saturated lower embankments and foundations as do Delta levees. Because there are over 1,100 miles of levees in the Delta, there is no one typical cross section of geometries and materials that is representative of all of the Delta levees. However, many levee reaches in the Delta are constructed of and/or are founded on saturated, sandy soils similar to those which liquefied at Solfatara and Moss Landing. While the heights of the Solfatara and Moss Landing embankments are generally about half the heights of typical Delta levees, general orders of magnitude for deformations would be expected to be similar for similar levels of earthquake shaking.

2.6 HISTORICAL SEISMICITY IN THE SACRAMENTO-SAN JOAQUIN DELTA

A review of available information indicates that between 1855 and 1989, approximately 55 earthquakes with magnitudes above 4.5 occurred close enough to the Delta to induce noticeable effects. However, none of these events are believed to have induced even moderate levels of shaking. The information indicates that the bedrock and stiff soil sites located at the periphery of the Delta have experienced peak accelerations no higher than about 0.1g to 0.15g. Within the central portions of the Delta, base motions would be expected to have been less than 0.1g. Even the 1906 San Francisco Earthquake is estimated to have generated peak accelerations of 0.08g or less within most of the Delta region.

2.7 PERFORMANCE OF DELTA LEVEES DURING PREVIOUS EARTHQUAKES

Reviews of newspaper accounts, engineering journals, and eyewitness interviews have shown that there is no evidence that a levee in the Sacramento-San Joaquin Delta has ever failed as a result of earthquake shaking. Moreover, there is no evidence of any Delta levee having experienced significant



FIGURE 3: 1940 FAILURE OF SOLFATARA CANAL LEVEE



FIGURE 4: 1989 FAILURE OF MOSS LANDING TIDE GATE EMBANKMENT

damage as a result of earthquake shaking. The most serious distress appears to have been the approximate 3 feet of settlement reported for a Santa Fe railroad bridge at the Middle River crossing during the 1906 earthquake. This lack of reported damage is not, however, indicative of a strong levee system. As noted above, the historical seismicity of the Delta is rather low and the level of shaking that has been experienced since island reclamation has been relatively small. Accordingly, the real meaning of the historical record is that the Delta levee system has never been subjected to significant earthquake motion and, in effect, has never really been tested.

It should be pointed out that the strongest earthquake loadings probably occurred during the 1868 Hayward (M=6.8) and 1906 San Francisco (M=8+) earthquakes. During these events, the levee system was not fully developed and the levees were generally less than half of their current height.

It should also be noted that while there is no evidence that any Delta levee has failed due to earthquake shaking, there has been over 140 levee failures and island inundations due to flood flows in the Delta since 1900.

3. SEISMIC ENVIRONMENT

3.1 ACTIVE FAULTS

The Sacramento-San Joaquin Delta lies in a seismically active region (see Figure 5). Most of the significant earthquakes which have occurred are associated with fault sources located to the west of the Delta area and are considered part of the San Andreas Fault system (see Figure 6). The San Andreas Fault system refers to the network of faults with predominantly right-lateral strike slip movement that collectively accommodate most of the relative motion between the North American and Pacific plates.

The Delta itself lies astride a physiographic boundary between the Coast Range and the Great Valley. This boundary also appears to represent a tectonic boundary characterized by a zone of thrust faulting, reverse faults, and folding (after Ake, et al., 1991). Many researchers have speculated that this zone may be capable of earthquakes similar to those experienced in Coalinga to the south ($M=6.7$ in 1983) and in Winters to the north ($M=6.5$ in 1892). Much uncertainty has surrounded the behavior and location of this potential earthquake source as it has very little surface expression and a very sparse record of seismicity. At least one researcher has indicated that it may be a 15-mile-wide zone of complex faulting running 400 miles along the western edge of the Central Valley. For presentation purposes, its inferred approximate location is shown in Figure 6 as a dotted line with the label of Coast Range Sierra Nevada Boundary Zone.

3.2 PROBABILITY OF FUTURE EARTHQUAKES

One of the ways used to predict future earthquakes is to examine the frequency of historical earthquakes, along with the rate of slip occurring along different faults. The U. S. Geologic Survey has been conducting such studies and one of the facts they have noted is that while the San Francisco Bay Region was very seismically active during the 1800s and early 1900's, there has been a period of relatively low seismic activity in the region since about 1911 (see Figure 7). This period of relative quiet appeared to have ended in 1979. Since 1979, there have been four moderate to large earthquakes in the region. The obvious possibility is that the region is about to enter a cycle of increased seismicity. In fact, as a result of their studies, the U. S. Geologic Survey predicted

SEISMIC STABILITY OF DELTA LEVEES

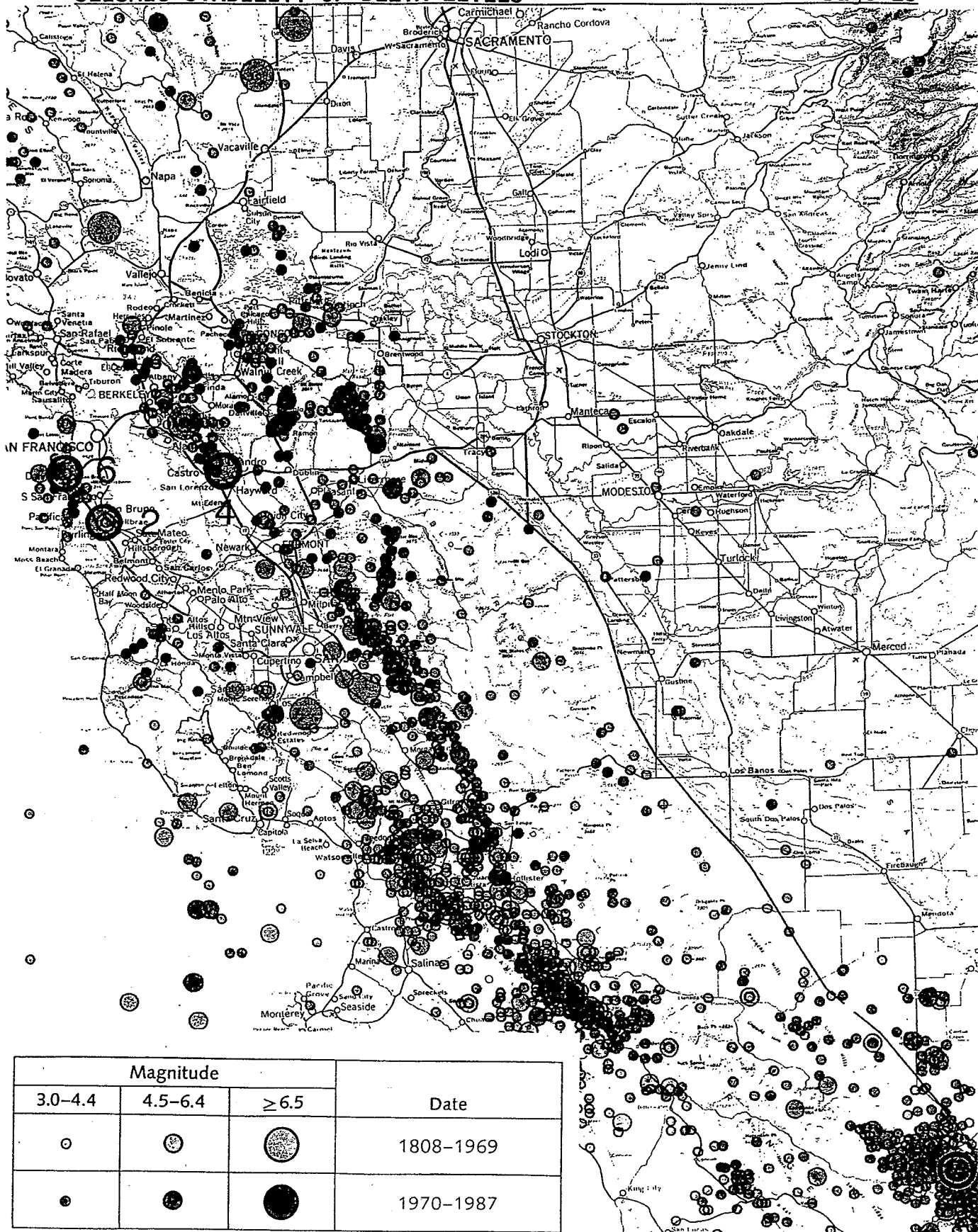


FIGURE 5: REGIONAL SEISMICITY (from USGS, 1987)

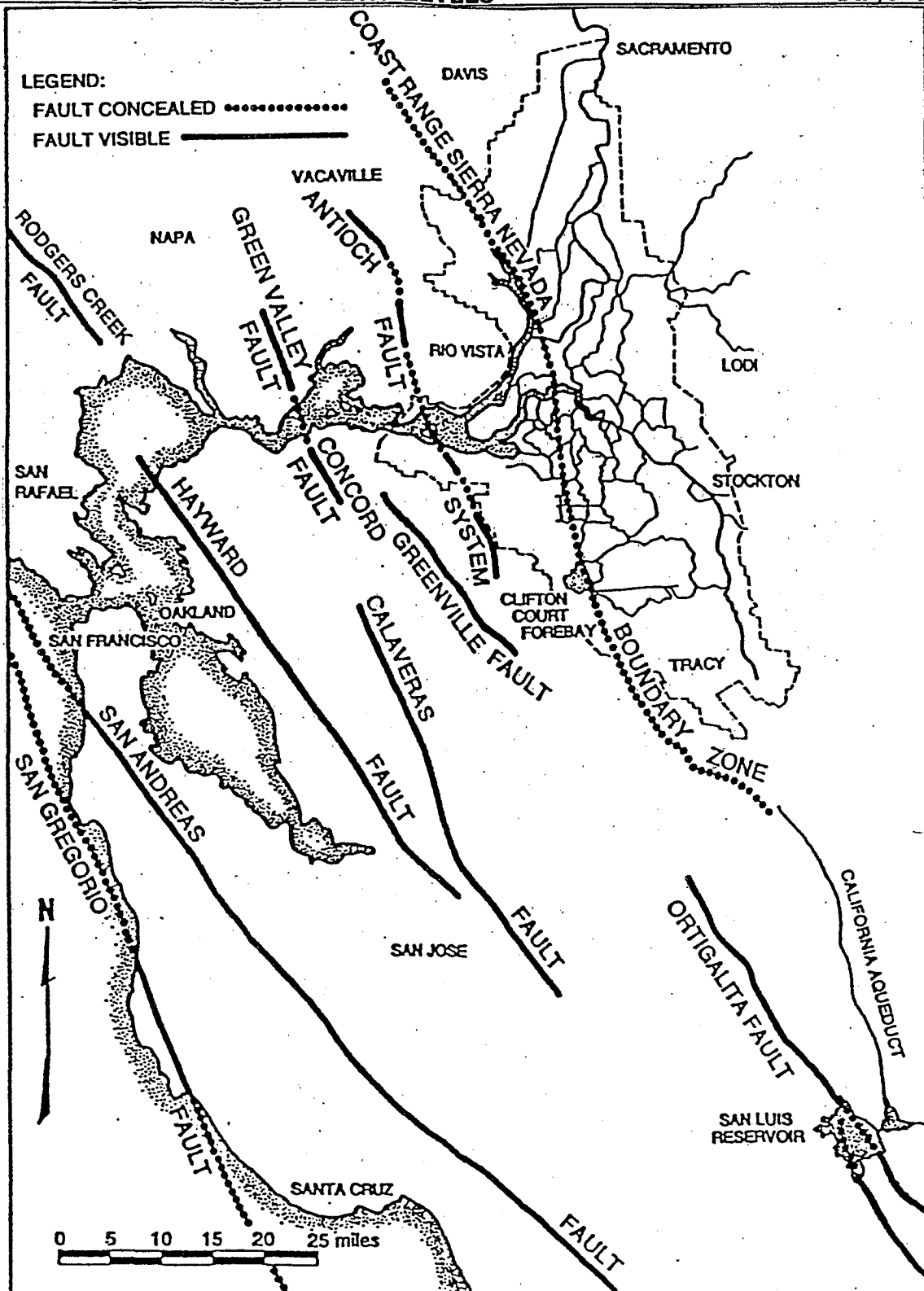


FIGURE 6: REGIONAL FAULT SOURCES (from DWR, 1992)

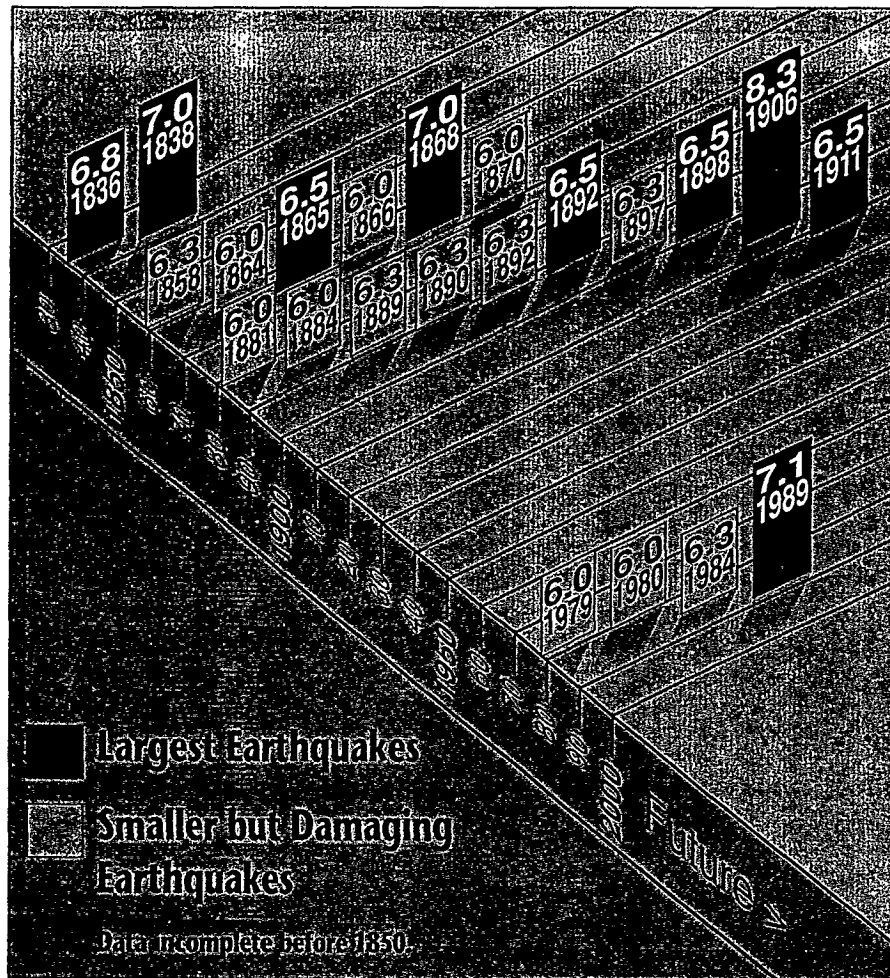


FIGURE 7: HISTORICAL REGIONAL EARTHQUAKES, (from USGS, 1991)

in 1991 that a Loma Prieta-sized earthquake (M~7) has a 67 percent chance of occurring within the next 30 years in the immediate San Francisco-Oakland area on either the San Andreas or Hayward Faults .

3.3 PROBABLE BEDROCK MOTIONS BENEATH DELTA WITHIN 30 YEARS

In an effort to estimate probable base motions beneath the Delta within the next 30 years, the Department performed a probabilistic risk analysis. This analysis provided probable peak acceleration levels that would be expected to develop in the bedrock and/or stiff soils lying at depth below the Delta. Several inputs including fault geometry, slip rate, distance from the Delta, maximum earthquake magnitude, and earthquake recurrence intervals were used to develop these estimates.

The results for a 50 percent probability of non-exceedance within an exposure period of 30 years are shown in Figure 8. These results are in the form of contours of peak bedrock acceleration. Predicted base motions range generally between 0.05g and 0.15g for this exposure period. These are relatively small levels of acceleration compared to those which would be predicted in the Bay Area during the same exposure period. As may be observed, the fact that the earthquake sources are generally located to the west of the Delta results in higher accelerations being predicted on the western edge of the Delta than on the eastern side.



4. GROUND MOTION AMPLIFICATION/DAMPING

4.1 AMPLIFICATION THROUGH SOFT CLAYS IN SAN FRANCISCO DURING THE 1989 LOMA PRIETA EARTHQUAKE

One of the most important lessons learned during the 1989 Loma Prieta Earthquake was that soft soils may significantly amplify earthquake motions by factors as high as three to five times the values experienced by more typical deposits. Shown in Figure 9 is the amplification documented at Treasure Island during the Loma Prieta event. The motions recorded on nearby rock (Yerba Buena Island) had peak accelerations of only about 0.07g. The motions recorded on Treasure Island, a hydraulic sandy fill placed over deep deposits of soft clay, had peak values of about 0.16g. This represented an amplification of approximately 2.5.

Similar amplifications were noted at several sites along the margin of the San Francisco Bay and were responsible for much of the prominent damage associated with the earthquake (e.g. Cypress Freeway Collapse). This type of amplification and consequent damage had previously been observed at soft clay sites in Mexico City during the 1985 earthquake. If motions throughout the Bay Area were as low as those recorded at the rock site at Yerba Buena Island, then much of the structural failures and damage would not have occurred. Thus, ground motion amplification through soft soils is an extremely important aspect of seismic loading.

4.2 DAMPING THROUGH SOFT PEATS IN UNION BAY, WA DURING 1969 EARTHQUAKE SEQUENCE

Some investigators have speculated that the soft, peaty soils in the Delta have the same amplification characteristics as do soft clays. As a result, many studies show relatively small bedrock motions being amplified up several times for use in design. However, this may not necessarily be correct if the soft soils in question are fibrous peats. Indeed, the only known earthquake records obtained from a recording site founded on peaty soils indicated severe attenuation or damping rather than amplification. These records were obtained at a site near Union Bay, WA, during a magnitude 4.5 earthquake which occurred about 25 miles away. As shown in Figure 10, downhole seismographs indicated damping factors of as much as 10 (amplification factors as low as 0.1) when ground motions propagated through 58 feet of unconsolidated peat. In effect, the fibrous peat acted as a base isolation system.

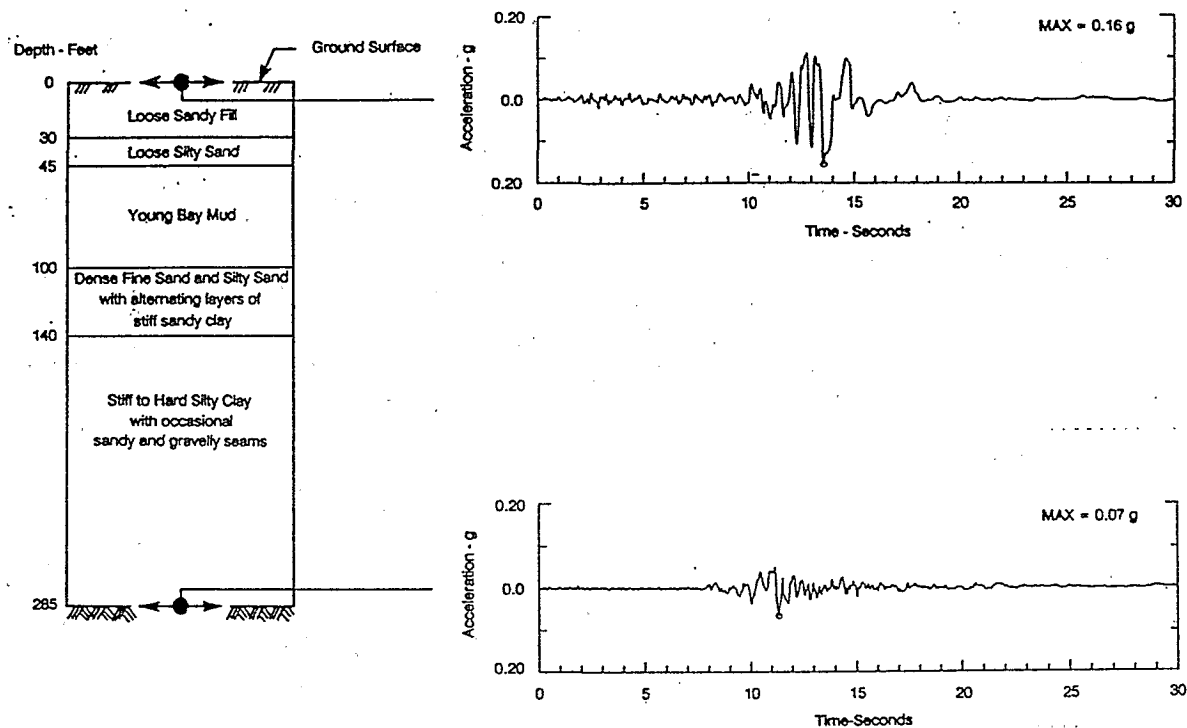
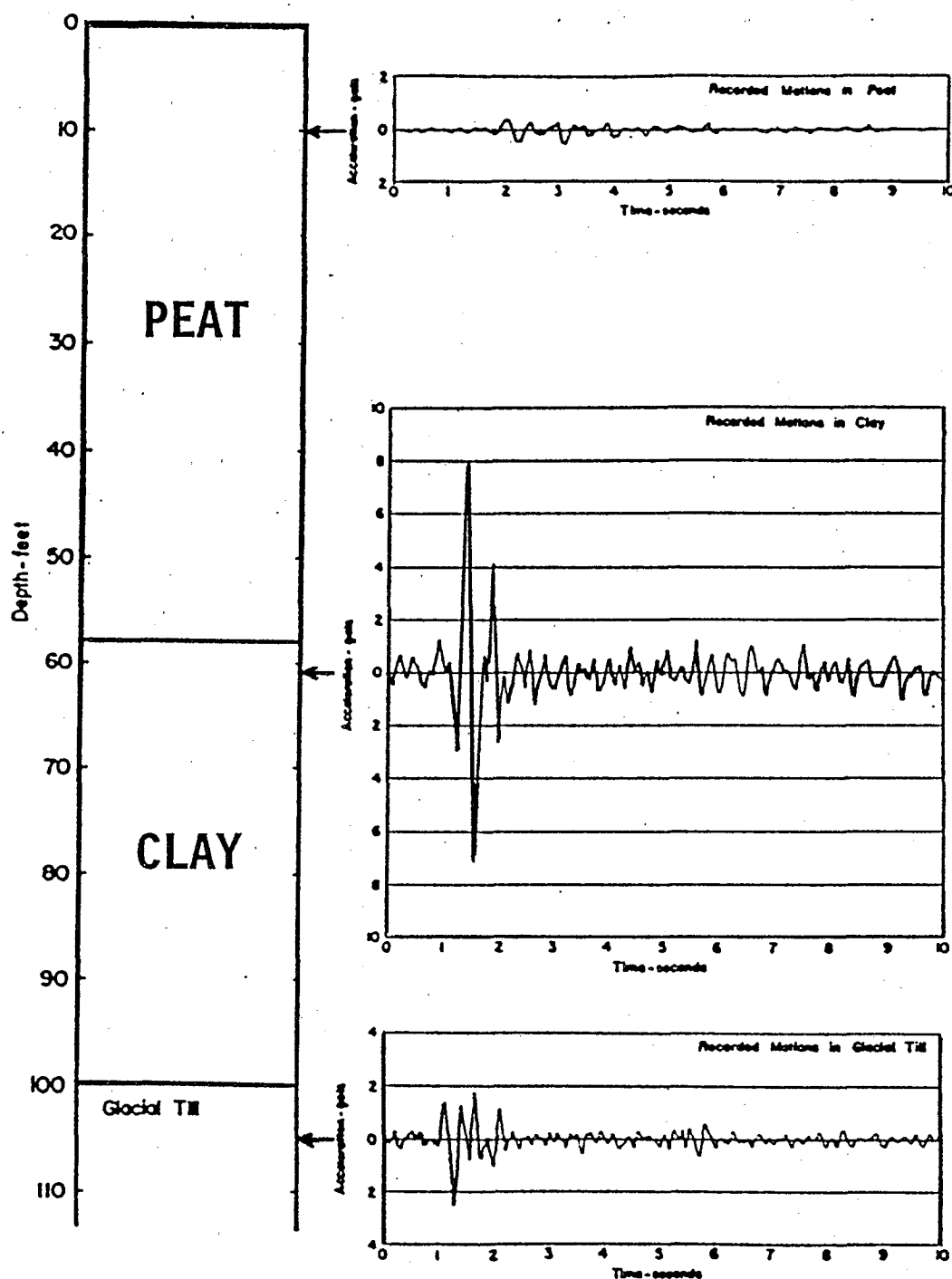


FIGURE 9: SCHEMATIC SOIL PROFILE AND SITE RESPONSE AT THE TREASURE ISLAND STATION (from Seed et al., 1990)



Recorded motions—EW components.

FIGURE 10: 1969 RECORDED MOTIONS FROM UNION BAY, WA
 (from Seed and Idriss, 1970)

4.3 IMPLICATIONS FOR DELTA LEVEES

Many levees in the Delta are founded on soft clayey and peaty soils. The data described in the foregoing sections indicate that such soils can either amplify motions by factors of 3, or dampen motions by factors of 10. With such potentially large values for modifying earthquake motions, the potential for the soft foundations beneath levees to either amplify or damp earthquake motions becomes the dominant element in assessing earthquake stability.

Many foundation deposits in the Delta, however, are somewhat different than sites in either San Francisco Bay or Union Bay. Delta sites may not generally have deep uniform deposits of soft clay, such as in San Francisco Bay. Nor are the peaty soils beneath Delta levees as fibrous or as weak as those in Union Bay. Consequently, the behavior of Delta deposits during earthquake shaking would be expected to be intermediate between the two extremes described above. There would also be expected to be some range in the types of amplification at different locations in the Delta. However, good evidence of their characteristic behavior during earthquake shaking simply does not exist at this time.

5. PREVIOUS STUDIES

5.1 GENERAL

Several studies and reports concerning seismic hazards and risk analysis have been previously prepared for the Delta region during the last 12 years by government and private concerns. These include the following 12 studies:

Geotechnical Investigation - Earthquake Safety Assessment of the Mokelumne Aqueduct - San Joaquin Delta Crossing (Earth Sciences Associates, 1992).

Preliminary Seismic Risk Analysis, North Delta (U. S. Bureau of Reclamation, 1991).

General Seismic and Geotechnical Risk Assessment, Sacramento-San Joaquin Delta, California (Dames and Moore, 1991).

Seismic Design Criteria, Wilkerson Dam, Bouldin Island, California - DRAFT (Harding Lawson Associates, 1990).

A New View of the Sacramento-San Joaquin Delta (B. J. Miller, 1990).

Preliminary Seismic Risk Analysis, South Delta (U. S. Bureau of Reclamation, 1989).

Estimated Performance of Twitchell Island Levee System (Michael Finch, 1988).

Sacramento-San Joaquin Delta Levee Liquefaction Potential (U. S. Army Corps of Engineers, Sacramento District, 1987).

Seismicity DRAFT (DWR, 1985).

McDonald Island Study, Levee Stability (Dames and Moore, 1985).

Earthquake Damage in the Sacramento-San Joaquin Delta (Michael Finch, 1985).

Mokelumne Aqueduct Security Plan (Converse Ward Davis Dixon, 1981).

SEISMIC STABILITY OF DELTA LEVEES

All of these previous studies are considered to be preliminary in nature due to the lack of reliable data for the vast Delta levee system. A general consensus among the investigators is noticeable on some of the issues concerning earthquake evaluations of Delta levees:

- o None of the reports could describe with certainty the amplification or attenuation characteristics of the Delta's organic soils. Some did not address this issue at all.
- o Essentially all of the reports state that liquefaction is likely to occur in the foundation soils beneath the organic soil layers. The reports find that, in general, the acceleration values required to trigger liquefaction are between 0.1g and 0.2g.
- o Larger acceleration values are anticipated in the southwestern portion of the Delta than in the northeastern part.
- o None of the studies reported a past levee failure due to earthquake shaking.
- o Most of the investigators recognized a need for additional studies before a more conclusive answer regarding the vulnerability to earthquake shaking could be determined.

Typical types of findings reported in previous studies are illustrated in Figures 11 and 12. Figure 11 shows the results of a liquefaction potential assessment made by the Sacramento District of the U. S. Army Corps of Engineers in 1987. For this assessment, available borehole exploration data was employed to predict the liquefaction potential of the Delta levees and foundations. This plot shows that the central portion of the Delta would be considered to have moderate to high potential for liquefaction. Other portions were considered to have low potential for liquefaction, or insufficient information available for a determination to be made.

Figure 12 presents a summary plot presenting the results from the 1992 Earth Sciences Associates evaluation of liquefaction potential along the Mokelumne Aqueduct. As shown in the figure, there is relatively high potential of liquefaction predicted along the western edge of the Delta within 30 years (about 90 percent probability). This potential generally decreases towards the eastern edge of the Delta.

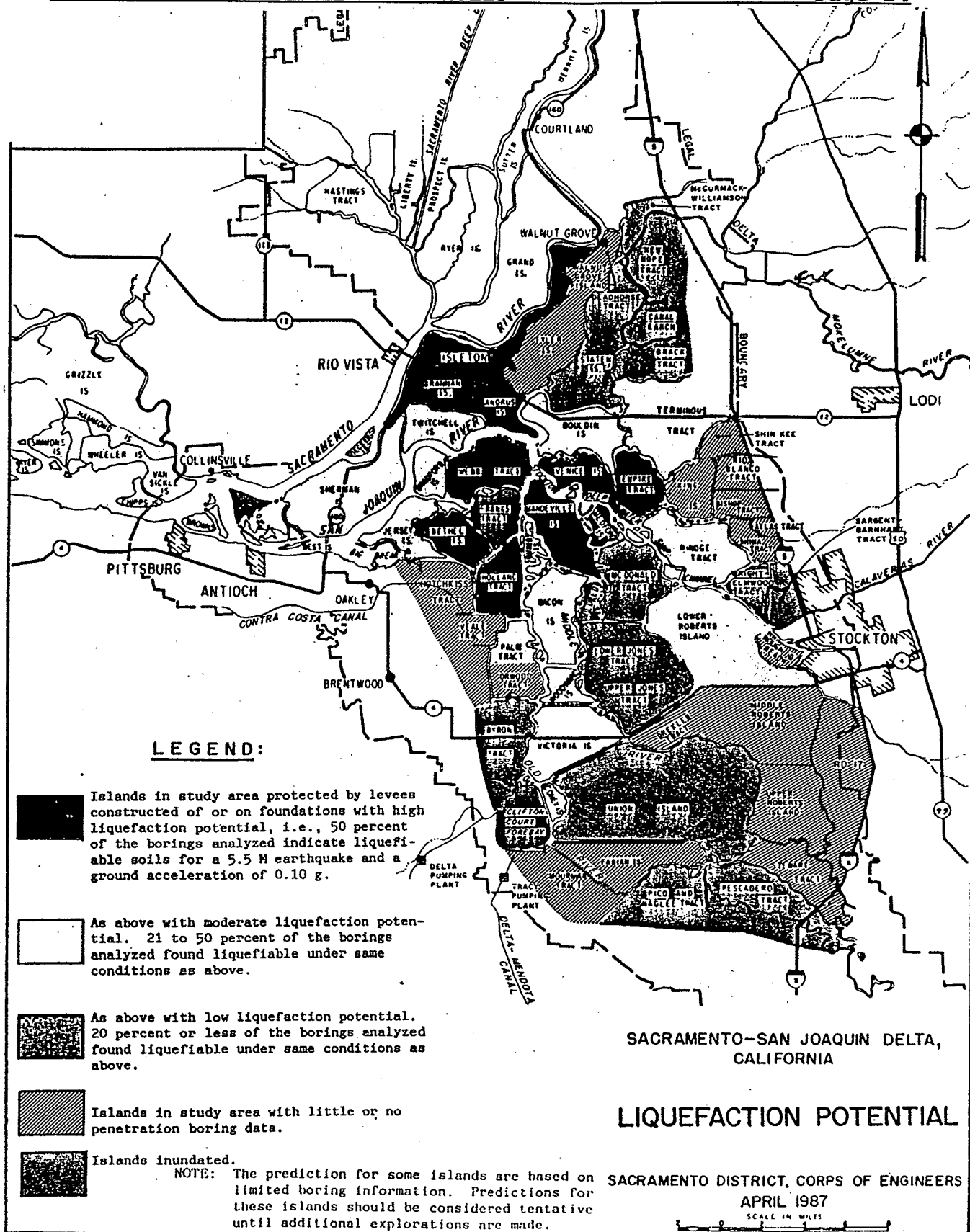


FIGURE 11: LIQUEFACTION POTENTIAL (from USACE, 1987)

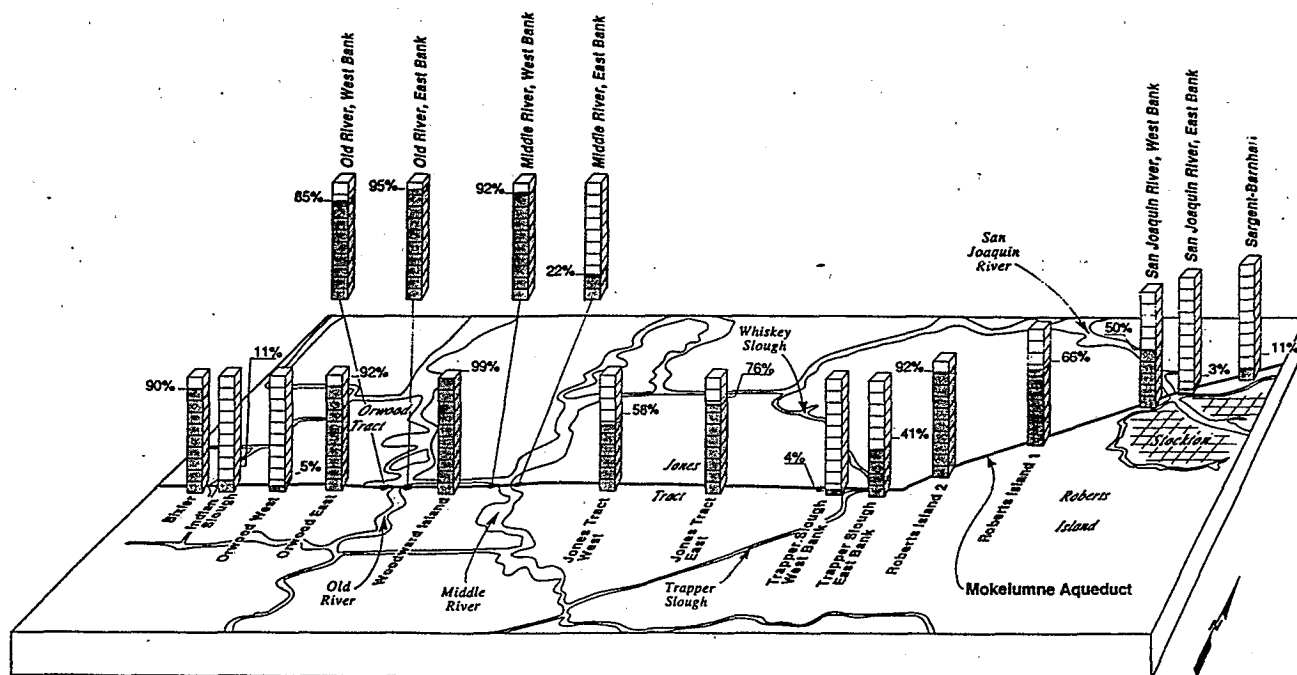


FIGURE 12: PROBABILISTIC LIQUEFACTION POTENTIAL (from Earth Sciences Associates, 1992)

6. PRELIMINARY ASSESSMENT OF LEVEE DAMAGE POTENTIAL

6.1 GENERAL

Precise predictions of performance for the vast levee system in the Delta during future earthquakes are not possible with the information available. With hundreds of miles of levees, variable geometries, variable levee materials, and variable foundations, the problem is simply too large and the information too incomplete to be conclusive for specific reaches. However, some insight can be gained by assuming a general level of behavior for levees, and to examine the potential for different levels of earthquake shaking to affect performance. To this end, the following criteria were used in delineating potential levee damage susceptibilities:

HIGH - It is likely that there would be widespread liquefaction of sandy and/or silty levees, probably resulting in sufficient losses of freeboard to cause overtopping and subsequent inundation of the island or tract. Extensive cracking leading to piping failures of the levees is also expected to be common in this area.

MODERATELY-HIGH - It is likely that isolated reaches of levees would develop extensive liquefaction and result in significant loss of freeboard. In such areas where levees also have relatively little freeboard and/or limited cross sections, overtopping and piping failures are likely.

LOW to MODERATE - Liquefaction of levee embankments may occur intermittently. In many locations there may be localized slumping and cracking similar to that which occurs during large floods. Levee failure may result if repairs are not made immediately.

LOW - Locations of liquefaction within levees are sparse and difficult to detect. Minor cracking and slumping may be reported. However, it will be difficult to ascertain whether they were pre-existing or a result of the earthquake. Some pre-earthquake seeps may change flow rates, or may even stop flowing. No major repairs would be expected as a result of the earthquake shaking.

6.2 PRELIMINARY ASSESSMENTS OF LEVEE DAMAGE POTENTIAL

Preliminary assessments of levee damage potential during future earthquakes are shown in Figures 13 and 14. The assessments were developed using the probabilistic bedrock accelerations shown in Figure 8 for a 30-year exposure period. Two alternative assumptions for ground motion amplification were used. In Figure 13, an amplification factor of 1.0 was assumed. In Figure 14, an amplification factor of 1.6 was used. These values represent our best estimates for ground motion amplification for Delta deposits and were derived from seismic response analyses and the past performance of the levee system.

The estimated zones of levee damage potential are not intended to imply that all levee reaches in the zones have the same susceptibilities. Rather, it is expected that at least some portions of each levee reach will have sufficiently liquefiable material to result in the susceptibility identified.

The preliminary assessments indicate that only the westernmost portions of the Delta have a moderately high probability of experiencing levee damage within 30 years if an amplification factor of unity is assumed (see Figure 13). However, if the amplification factor was increased to 1.6, the entire western half of the Delta is shown to have a moderately high susceptibility to levee damage (see Figure 14). The two plots together describe our current perception of the probable range in susceptibility for a 30-year exposure period. Although Figures 13 and 14 show that the western edges of the Delta appear to be vulnerable to future earthquake shaking, it should be noted that this assessment is not as pessimistic as other studies (e.g. see Figure 12). For higher exposure periods (e.g. 50 years or 100 years), the expected susceptibilities for levee damage and failure significantly increase.

6.3 DAMAGE POTENTIAL FOR EIGHT KEY WESTERN DELTA ISLANDS

Preventing the inundation of eight key western islands in the Delta is considered important in preventing salt water intrusion in the Delta. These eight islands are located on the most western portions of the Delta and are Sherman Island, Twitchell Island, Bradford Island, Jersey Island, Hotchkiss Tract, Webb Tract, Bethel Tract, and Holland Tract.

Unfortunately, their western locations also mean that they would probably be exposed to the highest levels of base

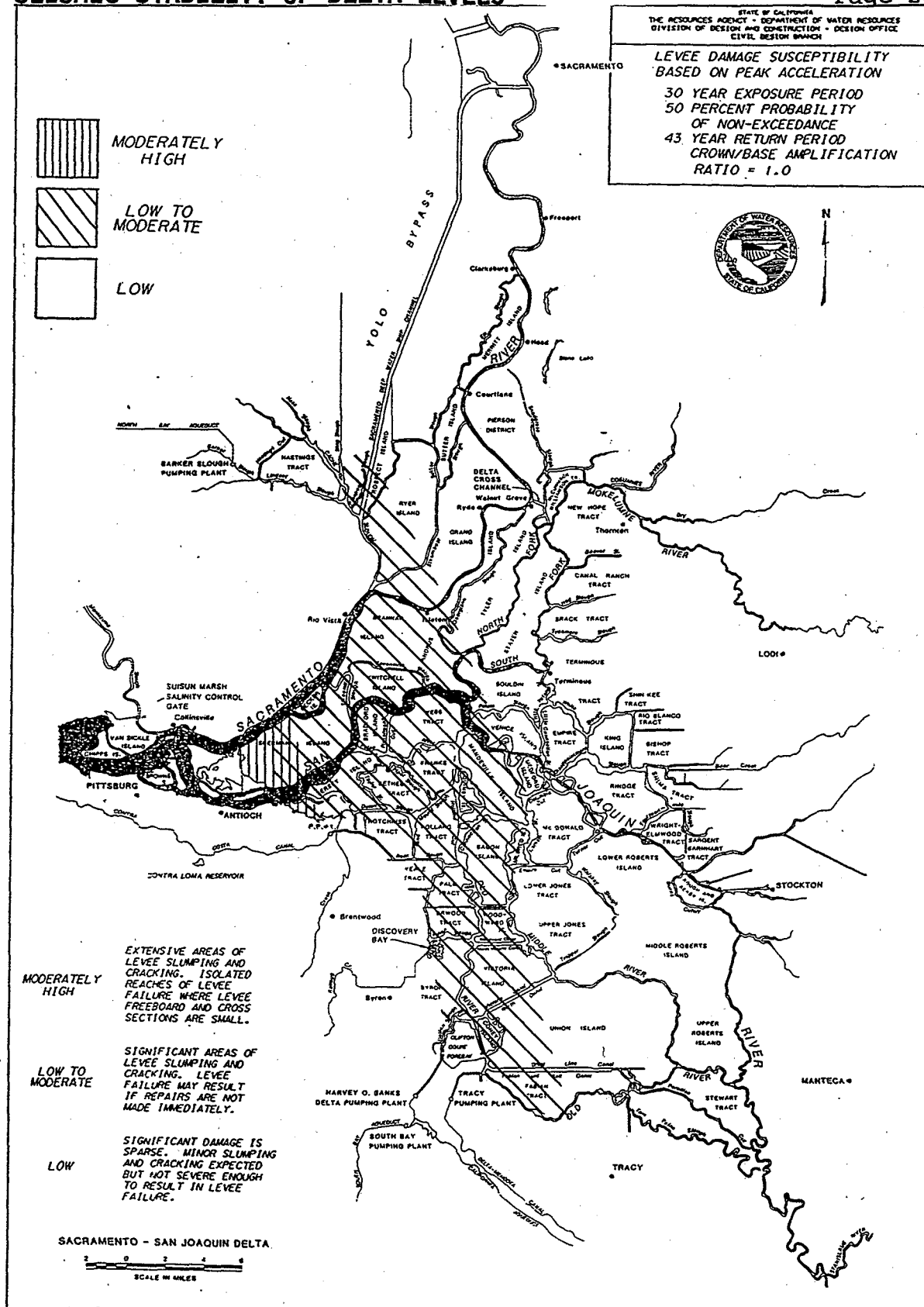


FIGURE 13: ESTIMATED LEVEE DAMAGE SUSCEPTIBILITY
(Crown/Base Amplification Factor = 1.0)

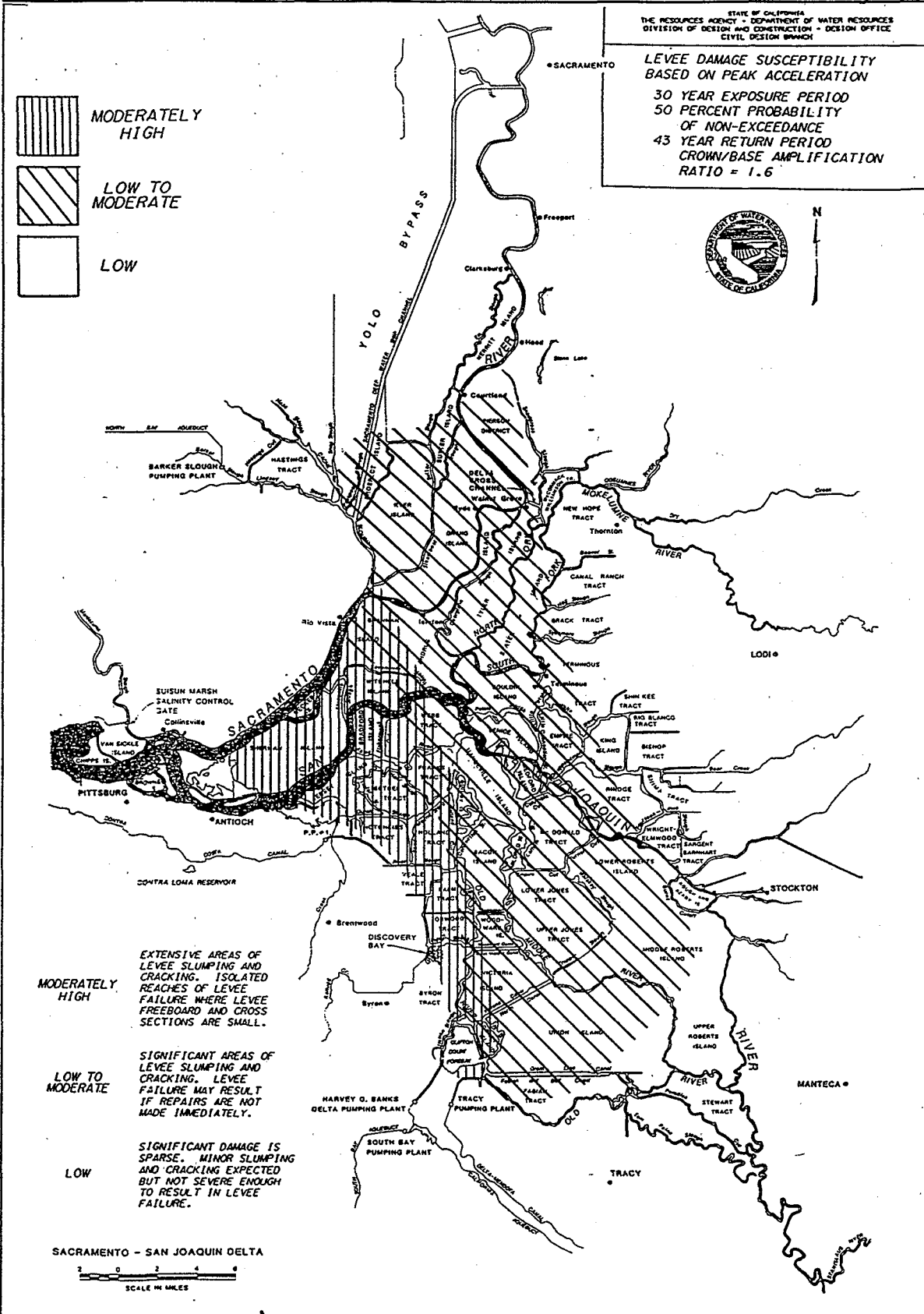


FIGURE 14: ESTIMATED LEVEE DAMAGE SUSCEPTIBILITY
(Crown/Base Amplification Factor = 1.6)

motion that the Delta might experience from future earthquakes. As stated previously, the western edge of the Delta is expected to experience higher levels of shaking due to the fact that the earthquake sources are generally located to the west of the Delta. The estimated damage susceptibilities plotted in Figures 13 and 14 reflect this result. Even for the lower amplification factor (i.e. amplification factor equals 1.0), Sherman Island is shown to be susceptible to moderately-high damage (see Figure 13). For the higher ground motion amplification shown in Figure 14, all of the eight key western islands are shown to be susceptible to moderately-high damage within the next 30 years.

Supporting this result is the 1987 U. S. Army Corps of Engineers evaluation of liquefaction potential showing that seven of the eight key western islands have a moderate to high potential for developing liquefaction (see Figure 11).

6.4 METHODS AVAILABLE TO STRENGTHEN LEVEES AGAINST EARTHQUAKES

Methods available to strengthen levees against earthquakes include the following:

- o In situ densification by vibrating probes or grouting to prevent liquefaction and strength loss. These measures are extremely expensive and are generally economically feasible only for limited reaches.
- o Increase the size of levees to increase stability and maintain freeboard in case of earthquake-induced settlement. This approach requires staged construction techniques and the addition of a substantial amount of fill which is already in short supply in the Delta.
- o Installation of cut-off walls and/or filters to mitigate the effects of cracking and internal erosion. This is also relatively expensive, but not as high as in situ densification.

Due to the long lengths of levees associated with each island, typically several miles, it probably is not economically feasible to remediate most levees to resist seismic shaking. At most, some key or extremely weak levee reaches might be treated. However, even the investigations required to determine which reaches are the worst and what type of treatment would be required could cost several million dollars for each island. This would be a separate cost from the actual treatment.

7. FUTURE STUDIES

7.1 PURPOSE AND NEED

It has not been the intention of the Department's seismic evaluations to either identify specific levee reaches for remediation, or design new levees to meet earthquake standards generally associated with dams. It is unlikely that most levee reaches can be economically upgraded to meet such criteria. Rather, the purpose of the seismic stability evaluations performed to date has been to develop information as to the susceptibility and opportunity for Delta levees to sustain damage during earthquakes. With this information, the degree of risk can be estimated in a general way and a rational approach can be pursued in the management of existing and future Delta facilities and resources.

During the course of the Department's preliminary evaluations, it became evident that it would be difficult to carry out seismic evaluations due to the numerous unknowns which could significantly influence the results. The unknowns which were identified as having the largest effects on assessments of levee stability during earthquakes are listed below in descending order of importance:

- A. Amplification/damping characteristics of shallow organic soils.
- B. Liquefaction resistance of levee fills.
- C. Strength loss potential in cohesive/organic soils following earthquake shaking.
- D. Amplification/damping characteristics of deep soil profiles.
- E. Liquefaction resistance of foundation soils.
- F. Probability of Coast Range-Sierra Nevada Fault Zone producing a large magnitude earthquake (M~6.5) within the Delta.

Several previous studies have also identified some of the above areas as requiring additional study. By far the most important is to determine the potential for Delta soils to either amplify or dampen out earthquake motions.

7.2 INSTALLATION OF SURFACE AND SUBSURFACE SEISMOGRAPHS

The Department is proceeding to install suites of surface and subsurface seismographs at four sites in the Delta to measure earthquake motions as they propagate through the soils beneath and through Delta levees. A typical suite of seismographs is shown in Figure 15, depicting three subsurface instruments beneath the levee at various depths together with a surface instrument on the levee crown. A schematic of the surface installation is also shown. The subsurface instruments will be installed in boreholes. Figure 16 shows the locations of the four downhole seismograph sites. Also shown are the locations of existing Department of Water Resources surface instruments located within and along the edges of the Delta.

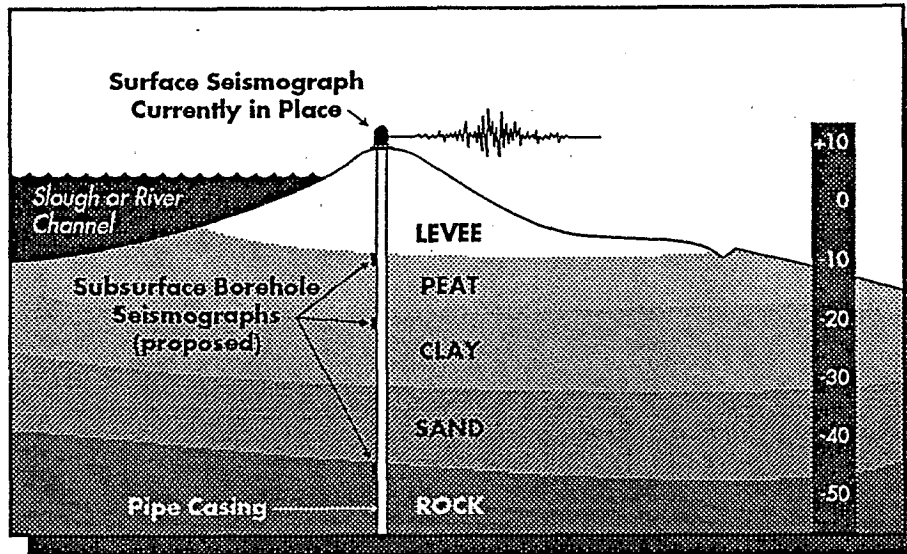
The purpose of the seismographs will be to use data obtained during small or distant earthquakes to predict performance of levees and other structures during larger or closer earthquakes. The data obtained will be used to:

- o Document characteristics of the earthquake motion.
- o Assess the ability of soft, organic soils in the Delta to amplify or dampen earthquake motions.
- o Calibrate the performance of levees and structures with different levels of earthquake motion.

Between 1979 and 1989, there were four earthquakes that would have yielded significant information had there been such instruments installed in the Delta. Since regional seismicity is not expected to diminish during the 1990s, it is reasonable to expect that, within 10 years, an earthquake will occur sufficiently close to provide such information. The installations are expected to be complete by February 1994 and the instruments are planned to be maintained for at least 10 years.

7.3 LABORATORY AND FIELD TESTING OF ORGANIC SOILS

In addition to the installation of seismographs, a limited program for investigating the dynamic properties of organic soils will be done concurrently with the placement of the instruments. Similar investigations have lead to the development of material properties characterizations which can be used analytically to predict behavior. For example, it is



The basic purpose of the seismic instrumentation is to use data obtained during small or distant earthquakes to predict performance of levees and other structures during larger or closer earthquakes. The data obtained will be used to:

- Document characteristics of the earthquake motion.
- Assess the ability of soft, organic soils in the Delta to amplify earthquake motions.
- Calibrate the performance of levees and structures with different levels of earthquake motion.

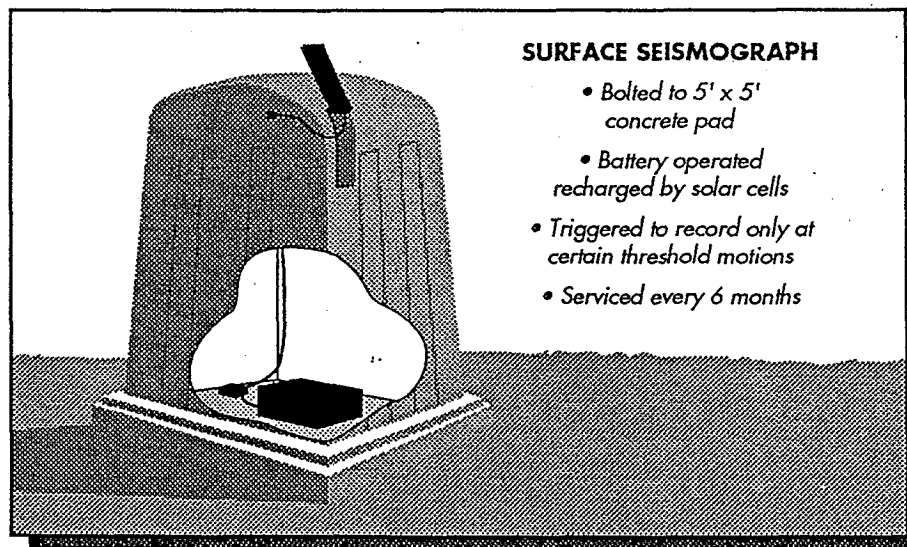
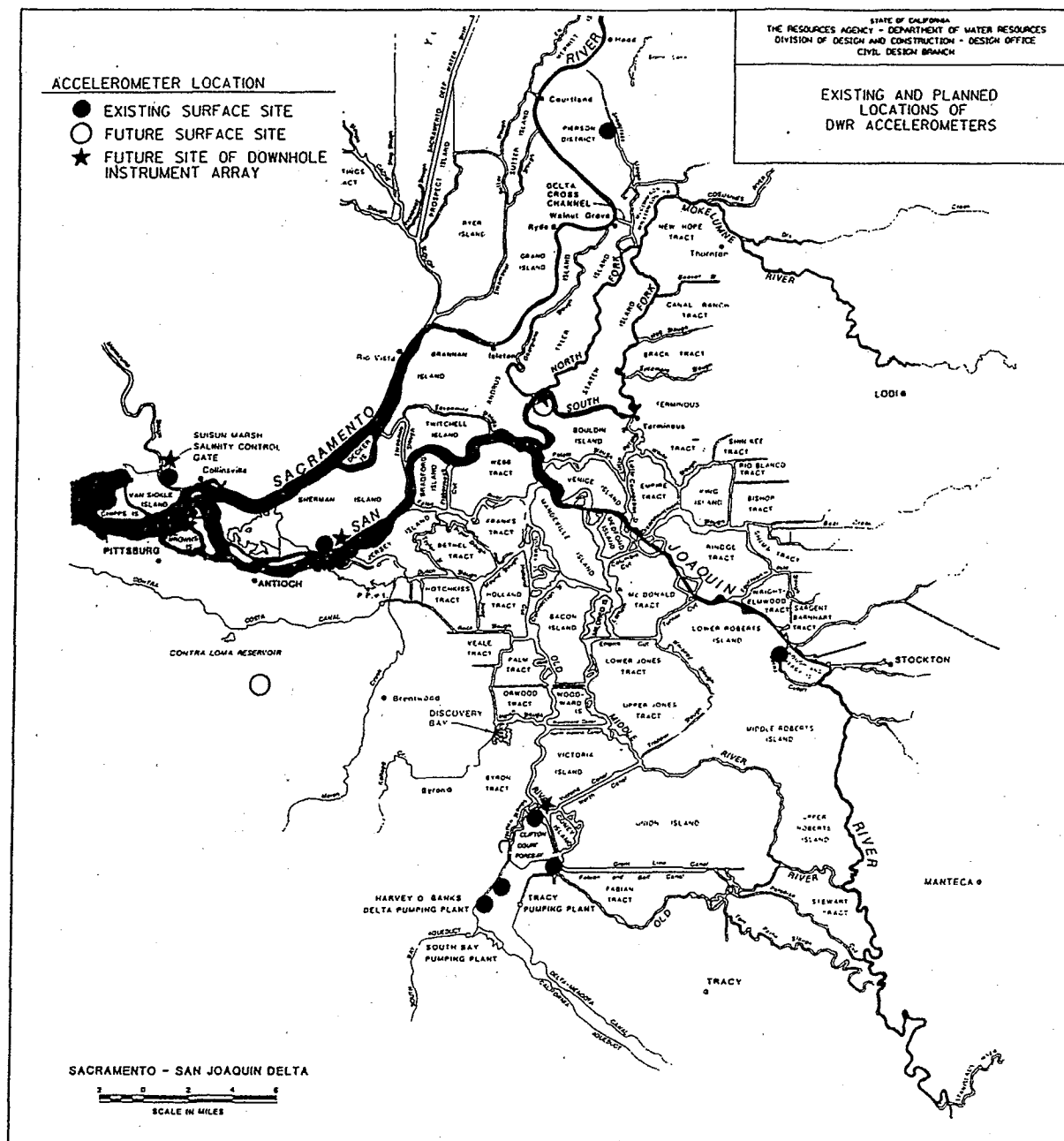


FIGURE 15: SCHEMATIC ILLUSTRATION OF SEISMOGRAPH INSTALLATION PLANNED FOR DELTA LEVEES



Instrument Location	Date Installed	Site Conditions
Peripheral Canal	1969	Alluvium
Delta Pumping Plant (2 devices)	1971/1973	Structure founded on rock
Calif. Aqueduct Milepost 1	1980	Canal cut slope in rock
Rough and Ready Island	1980	Structure founded on levee
Clifton Court Forebay	1983	Spoil fill over alluvium
Clifton Court Forebay - North Levee	1991	Levee overlying peaty soil
Sherman Island - South Levee	1991	Levee overlying peaty soil
Montezuma Slough - East Levee	1991	Levee overlying peaty soil

FIGURE 16: LOCATIONS OF EXISTING AND PLANNED SEISMOGRAPH SITES IN THE SACRAMENTO-SAN JOAQUIN DELTA

now possible to predict with computer programs the ground motion amplification which occurred along the margins of the San Francisco Bay during the 1989 Loma Prieta Earthquake. However, this required over 20 years of experience to develop such material characterizations.

The laboratory and field investigations currently scheduled by the Department will be of limited scope. These investigations are associated with the installations of the downhole seismographs and no strain-dependent dynamic properties will be developed under this program. However, the Department is investigating possibilities of conducting more extensive joint investigations with other agencies and universities. Such studies could include field and laboratory testing which would develop strain-dependent dynamic properties such as modulus degradation and damping characteristics. The development of such material characterizations could lead to more accurate predictions of ground motion amplification which would be very valuable when used in conjunction with the results of the anticipated seismographic data.